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A comprehensive study of the link between star-formation history and X-ray source populations in the SMC

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Abstract. Using *Chandra*, *XMM-Newton* and optical photometric catalogs we study the young X-ray binary (XRB) populations of the Small Magellanic Cloud (SMC). We find that the Be/X-ray binaries (Be-XRBs) are observed in regions with star-formation (SF) rate bursts $\sim$ 30–70 Myr ago, which coincides with the age of maximum Be-star formation, while regions with strong but more recent SF (e.g., the Wing) are deficient in Be-XRBs. Using the 2dF spectrograph of the *Anglo-Australian Telescope* (*AAT*) we have obtained optical spectra of 20 High-Mass X-ray Binaries (HMXBs) in the SMC. All of these sources were proved to be Be-XRBs. Similar spectral-type distributions of Be-XRBs and Be field stars in the SMC have been found. On the other hand, the Be-XRBs in the Galaxy follow a different distribution than the isolated Be stars in the Galaxy, in agreement with previous studies.

Keywords. stars: emission-line, Be, stars: formation, galaxies: individual (SMC), Magellanic Clouds, X-rays: binaries

1. Introduction: why observe the SMC?

The SMC is the best target to study a, as complete as possible, XRB population. Similar studies in the Galaxy are hampered by extinction and distance uncertainties. The Large Magellanic Cloud (LMC) is much more extended than the SMC, requiring large area coverage to obtain sufficient numbers of XRBs, while other Local Group galaxies are too far to reach the quiescent population of HMXBs (typical $L_X \sim 10^{32-34}$ erg s^{-1}; van Paradijs & McClintock 1995). This way we are able to construct the luminosity function of the HMXBs in the central region of the SMC (see Zezas *et al.*, these proceedings), and compare these luminosity functions with state of the art XRB synthesis models (e.g., Belczyński *et al.* 2008) and luminosity functions in other star-forming galaxies. In addition, the SMC hosts a large number of HMXBs (e.g., Haberl & Pietsch 2004; McBride *et al.* 2008; Antoniou *et al.* 2008a).

2. X-ray study of the SMC

Using the ACIS-I detector on board *Chandra* we observed 5 fields (P.I. A. Zezas) in the central part of the SMC (the so called SMC “bar”), with typical exposure times of 8–12 ks. These observations yielded a total of 158 sources, down to a limiting luminosity of $\sim 4 \times 10^{33}$ erg s^{-1} (in the 0.7–10 keV band), reaching the luminosity range of quiescent HMXBs. The analysis of the data, the source-list and their X-ray luminosity functions (XLFs) are presented in Zezas *et al.* (in preparation), while their optical counterparts and resulting classification are presented in Antoniou *et al.* (2008a).

Our *XMM-Newton* survey (P.I. A. Zezas) consists of 5 observations in the outer parts of the SMC, performed with the 3 EPIC (MOS1, MOS2 and PN) detectors in the full frame mode. The observed fields were selected to sample stellar populations in a range of ages ($\sim$ 10–500 Myr; based on the SF history of Harris & Zaritsky 2004). One of these fields was affected by high background flares and it is not included in the current study. We detected 186 sources down to a limiting luminosity of $\sim 3.5 \times 10^{33}$ erg s^{-1} in the 0.2–12 keV band. More details on the data analysis and the final source-list (including the XLFs) will be presented in Antoniou *et al.* (in preparation).

3. Candidate Be-XRBs

In order to identify the Be-XRBs that lie in our fields we first study the X-ray properties of the sources. Be-XRBs show pulsations and have hard 1–10 keV spectra (i.e. with a power-law energy index of $\Gamma < 1.6$; e.g., Yokogawa *et al.* 2003), which are signatures of accretion onto strongly magnetized neutron stars. This information is derived from X-ray spectral fits. However, for sources with small number of counts we use X-ray color–color diagrams (e.g., Prestwich *et al.* 2003).

The next step is the identification of an early (O or B) type star as the optical counterpart of these selected hard X-ray sources. We cross-correlate their position with optical photometric catalogs within a search radius calculated from the combination, in quadrature, of the astrometric uncertainty of the corresponding optical catalog, and the positional uncertainty for each X-ray source. In the present work, we have used two optical catalogs: the OGLE-II (Udalski *et al.* 1998) and the Magellanic Clouds Photometric Survey (MCPS; Zaritsky *et al.* 2002). In crowded fields, actual photometric (as well astrometric) uncertainties can be larger, due to source confusion, which we consider to be more severe in the MCPS catalog, due to the larger pixel size, and worse overall seeing. However, because of the incomplete coverage of the *Chandra* and *XMM-Newton* fields by the OGLE-II survey ($\sim$ 70% and $<$ 40%, respectively), we supplemented the optical data with the MCPS catalog, which fully covers the observed fields.

In order to identify an early-type counterpart, we use the locus of early (O and B) type stars in the V, $B-V$ color-magnitude diagram. We define this locus by using data from the 2dF spectroscopic survey of SMC stars (the most extended such catalog available; Evans *et al.* 2004). In addition, we perform Monte-Carlo simulations and we estimate the chance-coincidence probability for the O or B type stars to be $\leqslant$ 19% for the *Chandra* fields and $\sim$ 8% for the *XMM-Newton* fields.

Following the above approach, we find 9 and 7 new candidate Be-XRBs within the *Chandra* and *XMM-Newton* fields, respectively. Moreover, our results are consistent with previous classifications in all cases of overlap (18 for the *Chandra* and 1 for the *XMM-Newton* in total; all Be-XRBs). If we add to the above numbers the confirmed and candidate Be-XRBs that lie in our fields but have not been detected in our surveys (from the latest census of Magellanic Clouds HMXBs of Liu *et al.* 2005), we have a total of 29 and 9 Be-XRBs in the *Chandra* and *XMM-Newton* fields, respectively. We note that because of the transient nature of these systems, their numbers can be considered only as lower limits, but are nonetheless representative of the relative populations in the observed fields.

4. The “overabundance” of SMC Be-XRBs with respect to the Galaxy

It is widely accepted that the SMC hosts an unusual large number of HMXBs and Be-XRBs when compared to the Galaxy (see contribution by Coe, this volume). In order to investigate this, we have to minimize the age effects or variations due to SF rate differences for populations of different ages. This is feasible by studying the Be-XRBs with respect to their related stellar populations, i.e. the ratio of Be-XRBs to OB stars within an area. For the Be-XRBs in the *Chandra* SMC fields and the Galaxy we used sources with an X-ray luminosity limit of $\sim 10^{34}$ erg s^{-1}, while for the Galaxy we only kept sources within 10 kpc of the Sun. For the Galactic HMXBs we used the compilation of Liu *et al.* (2006), while for the SMC we supplemented the catalog of Liu *et al.* (2005) with our candidate SMC Be-XRBs (see §3). The OB stars for the SMC fields are derived from the MCPS catalog (based on the V magnitude and $B - V$ color), while for the Galaxy we used the compilation of Reed (2001).

We find that Be-XRBs are ~ 2 times more common in the SMC when compared to the Galaxy, thus *there is still a residual excess that cannot be accounted for by the difference in the SF rate.* However, this residual excess can be attributed to the lower metallicity of the SMC ($\sim 0.2\ Z_{\odot}$). Population synthesis models predict a factor of ~ 3 higher numbers of HMXBs in galaxies with metallicities similar to that of the SMC, when compared to the Galaxy (Dray 2006). In addition there is observational evidence for a trend of higher proportion of Be stars in lower metallicity environments (at least in the case of younger systems — Wisniewski & Bjorkman 2006; Martayan *et al.* 2007). We thus conclude that on its own, neither the lower SMC metallicity nor the enhanced SF rate at the age of ~ 40 Myr ago, can produce the observed 'overabundance' of SMC Be-XRBs (see also Antoniou *et al.* 2008a and McBride *et al.* 2008).

5. SMC X-ray source populations as a function of age

The SMC "bar" hosts young stellar populations (typically < 100 Myr; e.g., Harris & Zaritsky 2004), and the vast majority of SMC pulsars (Galache *et al.* 2008). Shtykovskiy & Gilfanov (2007) found that the age distribution of the HMXBs peaks at $\sim$ 20–50 Myr after the SF event, while McSwain & Gies (2005) observed a strong evolution in the fraction of Be stars with age up to 100 Myr, with a maximum at $7.4 < \log(\mathrm{age}) < 7.8$. These results motivated us to investigate the connection of the SF history of our *Chandra* and *XMM-Newton* fields with their population of Be-XRBs.

Using data from Harris & Zaritsky (2004) we derive the recent SF history in our *Chandra* and *XMM-Newton* fields, by calculating the average SF history of the MCPS regions ($\sim 12' \times 12'$) encompassed by them. We find that:

*(*i) For the *Chandra* fields, the most recent major burst peaked ~ 42 Myr ago, and it had a duration of ~ 40 Myr. In addition, there were older SF episodes (~ 0.4 Gyr ago) with lower intensity but longer duration, as well as a more recent episode (~ 11 Myr) observed only in one of the *Chandra* fields.

*(*ii) For one of our *XMM-Newton* fields, the most recent major burst occurred ~ 67 Myr ago. We also observed two fields with very young populations (most recent major burst at ~ 11 and ~ 17 Myr ago, respectively). Both these fields have additional less intense bursts ~ 67 Myr ago.

5.1. *Link between SF and the XRB populations*

In order to investigate the link between SF and the XRB populations, we calculate the average SF history for the MCPS regions ($\sim 12' \times 12'$; Harris & Zaritsky 2004) that host one or more Be-XRBs (candidate and confirmed) detected in our *Chandra* and *XMM-Newton* surveys. The SF history at each region is weighted by the encompassed number of Be-XRBs. We repeat this exercise for the MCPS regions that do not have any known Be-XRB in our surveys. The two SF histories are presented in Fig.1 (upper panel).

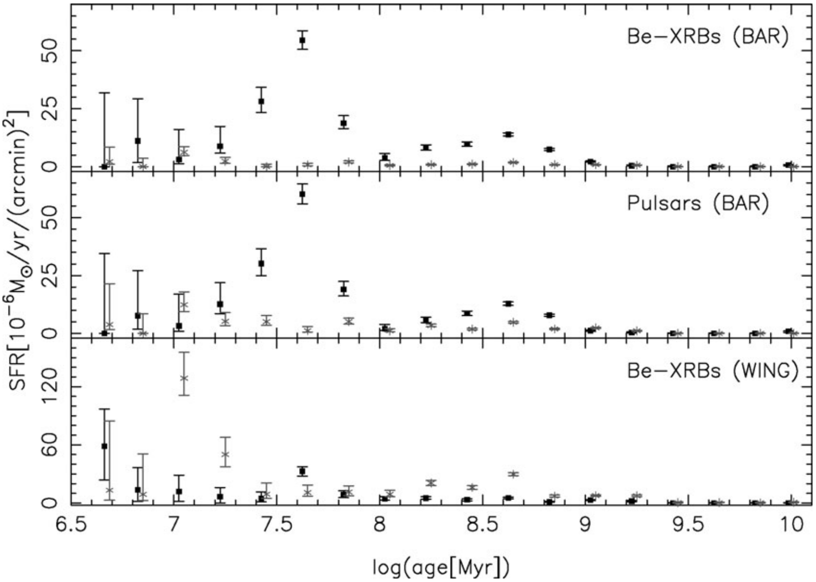

Figure 1. (*upper panel*) The average SF history for the MCPS regions (using data from Harris & Zaritsky 2004) which overlap with our *Chandra* and *XMM-Newton* fields and host one or more (shown in black) or none (shown in gray) detected Be-XRBs (candidate and confirmed). (*middle panel*) The same plot as above but for MCPS regions with and without X-ray pulsars, and (*bottom panel*) with and without Be-XRBs from the *Chandra* Wing survey (P.I. Coe, AO6). For clarity a small offset of log(age[Myr]) ∼ 0.025 has been applied in the distributions of areas without Be-XRBs and/or pulsars.

Following the above comparison, we construct (middle panel of Fig.1) the SF history for the MCPS regions (overlapping with any of our fields) that host one or more known X-ray pulsars† (shown in black), and for those that do not host such sources (shown in gray). A large fraction of these pulsars also appears in the Be-XRBs sample, since most of the companions of the SMC pulsars are Be stars. However, for completeness we present both (upper and middle panel, respectively), since the pulsars are X-ray selected while the Be-XRBs used above are selected based on the optical properties of the companion stars. In total, in our *Chandra* fields lie 19 X-ray pulsars, while in the *XMM-Newton* fields only 3. As expected, the pattern in their SF history is very similar to that of Be-XRBs. In Fig.1 (bottom panel) we also present the average SF history for the MCPS regions with any (shown in black) and without (shown in grayq) Be-XRBs detected in the *Chandra* Wing survey (P.I. M. Coe, AO6). This survey covered 20 fields, however 3 of those were not used here because they do not overlap with any MCPS region, while all 4 Be-XRBs are also X-ray pulsars (Schurch *et al.* 2007).

From the above analysis we find that the number of Be-XRBs peaks for stellar populations of ages $\sim 30-70$ Myr. This is consistent with the study of McSwain & Gies (2005), who find that Be stars develop their decretion disks at ages of ∼ 25–80 Myr, with a peak at ∼ 35 Myr. OB stars formed during this episode are expected to reach the maximum rate of decretion disk formation at the current epoch. We also find that the other two peaks (∼ 11 and ∼ 422 Myr) observed in the SF history of regions with Be-XRBs do not give any Be-XRBs as expected. The first one (at ∼ 11 Myr) is too early to give any pulsar

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† Using the on-line census of Malcolm Coe (http://www.astro.soton.ac.uk/∼mjc/ as of 06/05/2007).

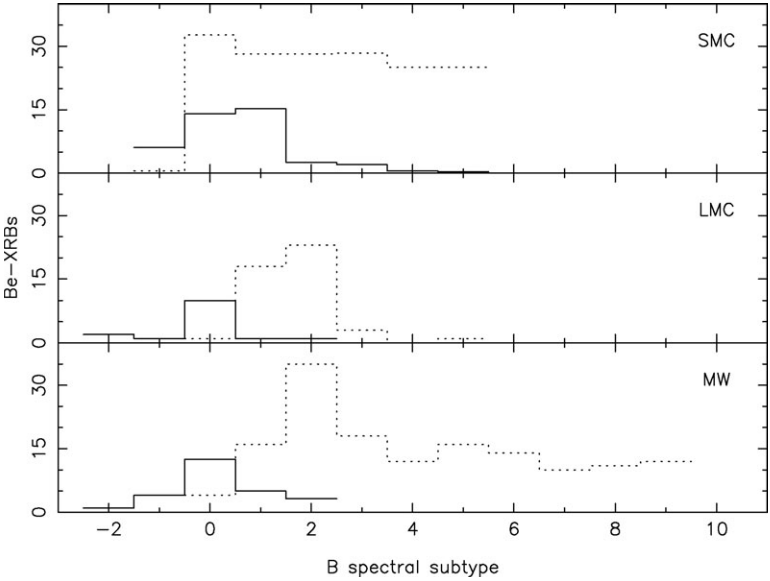

Figure 2. Comparison of the B spectral subtype distributions of Be-XRBs (solid histograms) to isolated Be stars (dashed histograms) in the SMC (top panel), the LMC (middle panel), and the Milky Way (bottom panel). Negative spectral subtypes correspond to O-type stars.

Be-XRB, while the second SF rate peak (at ∼ 422 Myr) cannot result in Be-XRB formation, since by that time all OB stars have become supernovae. The peak at ∼ 422 Myr ago is also observed in the global SF history of the SMC, and it temporally coincides with past perigalactic passages of the SMC with the Galaxy (Harris & Zaritsky 2004). A similar study by Shtykovskiy & Gilfanov (2007), reached the same conclusions, however these authors did not attribute the large number of SMC Be-XRBs to the timescale of maximum Be star formation.

Furthermore, the lack of a large number of Be-XRBs in the SMC Wing is consistent with the present study. As it is shown in Fig. 1 (bottom panel), the Wing has a weaker than the "bar" SF burst at the age of enhanced formation of Be stars (i.e. at ∼ 42 Myr), while its most recent intense SF burst occurred only ∼ 11 Myr ago. Thus we do not expect a significant number of SMC Wing Be-XRBs, at least comparable to that in the SMC 'bar'. Since in the present study we used the number of Be-XRBs from a single observation of each field and for fields covering both the SMC "bar" and the Wing, we were able to minimize the effects of the transient Be-XRB nature.

6. Optical spectroscopy of 20 SMC Be-XRBs

Using the 2dF spectrograph of the AAT we observed 20 HMXBs (Antoniou *et al.* 2008b) detected with *Chandra* (Zezas *et al.*, in prep.) and *XMM-Newton* (Haberl & Pietsch 2004). All of these sources were proved to be Be-XRBs. The spectral classification of 6 previously classified Be-XRBs have been revisited, while we estimate that our spectral types are accurate to better than ±1 subclass in most cases, especially for earlier than B2 spectral types.

The distribution of spectral types of our Be-XRB sample shows a peak at B1.5. In Figure 2 we present the B spectral subtype distributions of Be-XRBs (solid histograms) and of isolated Be stars (dashed histograms) in the SMC (top panel), the LMC (middle panel), and the Galaxy (bottom panel). Negative spectral subtypes correspond to O-type stars. Whenever only a broad spectral class was available, we equally divided the contribution in the different subtypes. We find similar spectral-type distributions of Be-XRBs and Be field stars in the SMC. On the other hand, the Be-XRBs in the Galaxy follow a different distribution than the isolated Be stars in the Galaxy, in agreement with previous studies.

This work also reinforces the $P_{\rm orb}$–Hα equivalent-width relation that holds for Be-XRBs. As Reig (2007) explained, the neutron star does not allow the companion star to develop a large decretion disc in cases of small orbital period systems, thus its presence leads to the tidal truncation of the disc, and this in turn to smaller Hα EW values. This is the first such study which demonstrates the importance of the Be-XRBs as a dominant component of young XRB populations.

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